Electromagnetic processing – from AC to DC Field
A way for process improvement and innovation

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Abstract

Technology of Electromagnetic processing of Materials (EPM) is relatively well known and mature. This knowledge gives the possibility to improve such processes and to integrate them in specific application (aeronautics, automotive sector, metallurgy...) at industrial scale. Thanks to a transverse and multiphysics approach which combined fluid dynamics, heat transfer, process metallurgy, solidification…, it is possible to know how to design new innovative processes with the integration of new design of electromagnetic system. An association of more complex EM configurations can be achieved: combination of AC and DC field, or two AC field…

Future development of EPM technologies are in agreement with energy savings and CO_2 reduction demand. In metallurgy industry, the integration of EPM technologies is more basically associated with productivity improvement, maintenance reduction and also safety consideration. EM processing can be classified by type of magnetic field involved: from AC to DC field. The choice depends on the desired action on the electro conductive materials. These processes are suitable for heating, melting, flow and shape control, solidification control (stirring, pumping)…but for each application a specific configuration needs to be defined, selected and optimized.

This paper gives some examples of EPM technologies applications for the development of new industrial process and main challenge to succeed in order to be relevant: (i) cold crucible technology or levitation, (ii) electromagnetic pump and (iii) DC electromagnetic brake. A combined approach by using numerical multiphysics modeling and experimental validation is used in order to give some guidelines for process improvement, or new electromagnetic design: feasibility and potentiality for integration at industrial scale.

Key words: electromagnetic processing, cold crucible, electromagnetic pump, traveling magnetic field, electromagnetic brake,

Introduction

EPM technologies are good candidates in industry for energy savings thanks to the replacement of fossil energy by using electrical energy [1,2].The European requirement for the climate (so called 20-20-20 climate package for 2020) defined goals for energy savings, CO_2 emission reduction, renewable energy use. The energy savings potential in industry are estimated at 20% of the energy consumption by using the Best Available Technologies (BAT); EPM is considered as one of the Best Available Technologies (BAT) and more precisely induction heating is defined as a solution for furnace and dryers improvement (31% of potential savings by replacement of conventional burners in metallurgy: heat treatment, melting process) in association with energy management, process integration and energy recovery. In France, according to EDF study [2], the use of induction can generate a potential energy savings of around 3 TWh/year. The main advantages of induction is a good energetic efficiency (direct and fast heating with no thermal inertia) and without pollution (vacuum furnace and no use of ceramic crucible). It's still necessary to defined new electromagnetic system: more efficient in terms of energy consumption with more flexibility or more integration in the process line. But in industry, Innovation and R&D development are driven by cost reduction which can be obtained by productivity improvement, maintenance reduction, and integration of recycling. Safety considerations can be also criteria to facilitate new EPM technologies development.

A basic classification from AC to DC field was considered from power source which generates alternative field (with a frequency ranging from several hundred kHz to several Hz): single phase field or multiphase field -traveling magnetic field (TMF) up to DC device with permanent magnets [3]. The main function of Electromagnetic processing is based on heating, melting, stirring, pumping for fluid flow control or suppression, coating or solidification control, etc…

In this paper, an overview of such device was given and illustrated with three examples: (i) cold crucible, (ii) electromagnetic pump and (iii) and electromagnetic DC brake. A linked is done with the application sector (aeronautics, nuclear and automotive for metallurgy industry) and type of application (melting and coating).

EM processes applications and potential improvement: from AC to DC field

AC high frequency field:

Cold crucible: In metallurgy industry, further works have to be performed for induction melting processes in terms of energy savings and particularly with cold crucible. Cold crucible is a common device for melting high reactive alloys (titanium, zirconium alloy, titanium aluminide, silicon…), with no pollution. But so far industrial use at large scale remain limited due to poor energetic efficiency [4], limited overheating (from 30 to 60°C which is very restrictive for investment casting) and technological difficulties for upscaling (industrial cold crucible design presents a size limitation around 10l of metallic alloy and require high power source around 1300kW). The better comprehension of this process thanks to recently improved multiphysics modeling tools and experimental measurements gives some guidelines for experimenting new kinds of cold crucibles. These elements were presented in a previous paper [5]: numerical modeling and first tests operated on a ‘thin shaped cold crucible’ seems very promising concerning the efficiency improvement and also a better overheating of liquid charge (Figure 1). It demonstrates the potentiality to improve the energetic efficiency of levitation cold crucible (hemispherical shape) which is very low: less than 20% of the power input for classical design compare to an expected efficiency of 35% for new design. The main challenge is actually to solve technical difficulties in order to construct these more complex thin designs by maintaining an efficient water cooling of each copper segment of the cold crucible. More works by coupling experimental design and modeling is needed to improve levitation at the bottom and define new technical solution, more particularly if we want to use at industrial scale bottom pouring device to transfer the melt into the mold. A significant efficiency improvement can also be obtained by optimizing the magnetic field distribution thanks to flux concentrator arranged around the coil [6].

New specific process can be derived from classical cold crucible device. A Metal Matrix Composites (MMC) processing for turbine blades (EGV process - Snecma Patent [7]) is an example. Figure 2 shows a typical levitation cold crucible device used to coat a ceramic fibre (SiC/C fibre). Thanks to the gap between each copper sector, the fiber is running at high speed (around 3 m/s) through the titanium melt maintained in semi-levitation. These process involved multiphysics phenomena: hydrodynamics (hot-dip coating, instabilities), wetting and interfacial reactivity of titanium and electromagnetic control of the charge stability, control of melt temperature. A good understanding of all effects gives the possibility to have a stable and continuous process thanks to titanium powder alimentation.

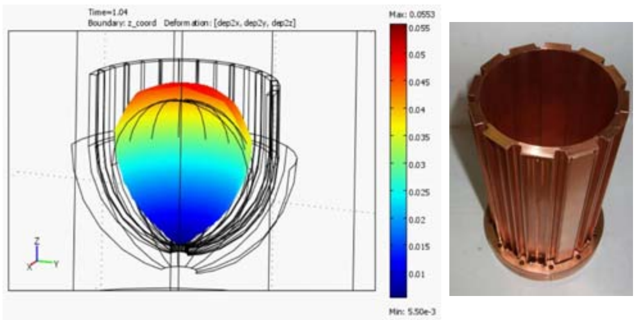

Fig. 1: Numerically calculated steady state shape of a liquid titanium charge for thin-Levitation melting crucible and example of thin shaped design of straight cold crucible [5].

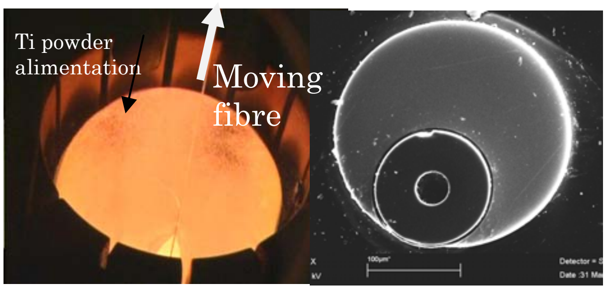

Fig. 2: cold crucible device used for coating SiC/C fibre with a titanium alloy (200g) and SEM cross section of Ti matrix metal composite filament [7].

Cold crucible is also used to melt poor conductive materials. In nuclear application, cold crucibles demonstrate its ability for nuclear waste vitrification with an implementation at industrial scale in 2010(La Hague, France [8]) which permits waste retreatment at higher temperature and reduce maintenance (increase the cycle life of the crucible).

Levitation: Electromagnetic levitation (EML) is commonly used for thermophysical properties measurements with small liquid droplet (a few mms in diameter) but the extension of such device for industrial remains limited. Electrode Induction Melting Gas Atomization (EIGA) is an example of application with a lot of benefits: robust, simple, safe process [9]. It is an innovative production method for metal powder from reactive and refractory alloys (for powder metallurgy and additive manufacturing). Recent developments are focused on increasing the melt flow rate and increasing rods diameter to use directly VAR electrode feedstock [9].

The use of container less system like electromagnetic levitation can be useful for high overheating with large energetic efficiency (no power losses in the cold crucible). But with classical EML system it is not possible to have large scale device (levitation larger than 1kg) due to difficulty to have a stable liquid charge with no leakage at the symmetric axis (no EM forces and not enough surface tension to counterbalance gravity). It was demonstrated in a previous paper [10] that the design of the coil helicity can generate torque on a metallic sample (solid state) and can initiate rotation and instabilities. An optimization of coil design minimized this effect but some fluid flow instabilities remain. That is why a combination of EM process are investigated by using DC fluid to damp the fluid flow [11] or a combination of AC device (a two-frequency horizontal field proposed by Spitans et al [12]) to have a drip and leakage free EM levitation melting. An example of application of such system is an original method for zinc coating developed by Tata steel and Posco [13]. An EML device and PVD coating is associated. It is based on evaporation of liquid metal (strong overheating of the droplet) and vapor deposition on the strip thanks to a distributive box. Main advantage is the ability to have low coating (less than 5 microns) and also possibility to use Zn-Mg alloy with different composition for a better corrosion resistance. To succeed in this direction, the main challenge was to limit or suppress instabilities for large volume of charge since remaining instabilities lead to an explosion of the liquid droplet.

AC-low frequency –Multiphase (TMF): Electromagnetic pump (EMP)

Another challenging aspect in nuclear application concerns the development of 4^{th} generation of nuclear power plant. The French Atomic Commission (CEA) is now engaged in the development of the pilot plant ASTRID (prototype of Sodium Cooled Fast Breeder Reactor). There is a recent interest on the development of large-size Annular Linear Induction Pump (ALIP) for nuclear engineering applications [14]. The potential use of large electromagnetic pump as circulating pump for the sodium contained in the secondary circuit in replacement of classical mechanical pumps is studied. To ensure a sufficient heat transfer through the secondary circuit, EMP needs to generate very high flow rate (2-4m^3/s). EMP presents different technological advantages (simplification, maintenance reduction, safety improvement: no mechanical parts in contact with sodium, no cooling water circuit). First modelling study was needed to consider MHD effects resulting from the strong coupling between electromagnetic and fluid flow in order to evaluate the pump efficiency and potential instabilities generate by the ALIP pump [15]. In parallel an instrumented facility (PEMDYN prototype 2m length) is under construction at CEA to get data for validation and give guidelines for upscaling at larger size (4-5m length).
Due to convection (high Reynolds magnetic number), significant end effects are observed for large velocities with entrainment of magnetic field line outside the pump (Figure 3) but also at the inlet inside the pump. This leads to the existence of regions where the axial force is negative at high velocities (Figure 4). Another phenomenon is the Hartmann effect which occurs near the walls at high fluid flow velocity. It leads to an expulsion of the electric current and the corresponding forces near the wall in a thin Hartmann layers due to the strong coupling between velocity and magnetic field.

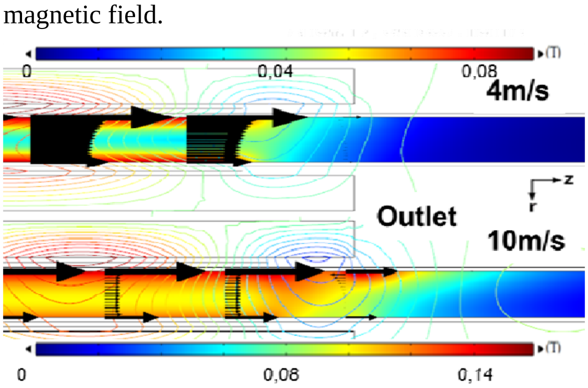

Fig. 3: Distribution of the magnetic field as well as the axial electromagnetic force component in the channel for two mean velocities, U = 4 and 10 $m.s^{-1}$ [16].

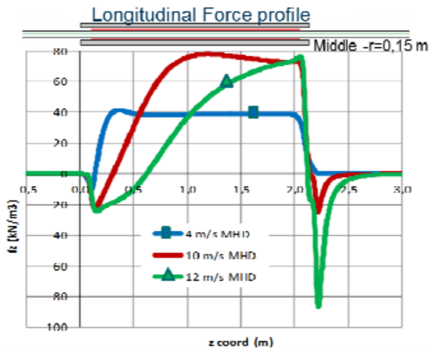

Fig. 4: Profiles of the axial component of the electromagnetic force along the channel centerline for various mean velocities [16]

DC field: Electromagnetic brake principle

In automotive sector and more particularly for galvanizing lines, a challenge is to be able to increase the line productivity by increasing strip velocity (two times faster) and maintaining a small coating thickness of zinc for corrosion protection. Different types of electromagnetic processes were evaluated and tested in the past with no success due to galvanealing (with HF inductor), stability and homogeneity of the coatings. New innovative process was evaluated by using more complex system: electromagnetic braking device (thanks to the generation of TMF with electrical system or mechanical rotor with magnet…). A new innovative approach developed in collaboration with Primetals Technologies (formerly Siemens SVAI) and Arcelor Mittal is based on a DC device for controlling zinc coating thanks to braking effect generate by magnets [17]. In hot dip galvanizing lines, zinc coating thickness control is realized by using gas knives wiping device. But for high velocities (> 3 m/s) a strong liquid zinc splash risk exists due to the necessity to increase the gas pressure for maintaining the same coating thickness. This is why an alternative approach with a complementary electromagnetic wiping system was studied based on the use of a DC field electromagnetic brake (EMB) system built with permanent magnets (Ne-Fe-B). The wiping effect on the liquid zinc was proved and is in good agreement with models descriptions (Figure 5, time-dependent 2D multiphysics electromagnetic /fluid mechanics coupled numerical model including an ALE deformed mesh technique). The main advantage of such device is a compact design and no overheating of the strip. This seems promising for an implementation on industrial line.

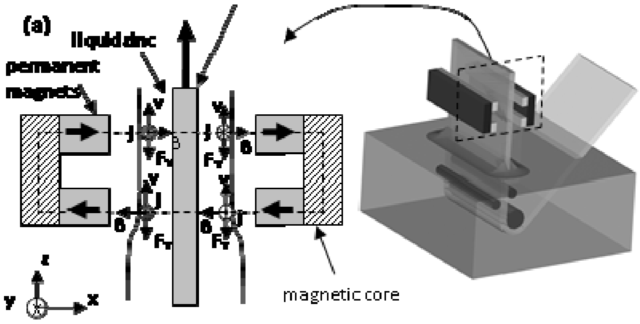

Fig. 5: Electromagnetic brake (EMB) configuration and geometry description [17].

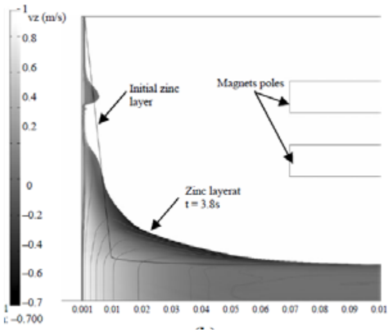

Fig. 6: Free surface and velocity field (streamlines) with (b) magnetic field at t=3.8s [17].

Conclusions

This paper gives an overview of EPM from AC to DC field thanks to examples of potential industrial processes. It demonstrates also the necessity of EPM process improvement of common device in order to be more use in industrial scale. For cold crucible, the main challenge is to improve its energetic efficiency and overheating capacity. A thin-shape cold crucible is a good candidate to improve significantly these two points. EPM technologies give a lot of possibilities for acting on electro conductive materials. To propose new innovative concept; the better understandings of each configuration allows us to figure out more complex system and define design for specific industrial needs. A multiphysics approach in combination with numerical modelling, give us an opportunity to evaluate the feasibility of such equipment and tools to optimize the design for industrial integration.

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